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UTILIZATION OF NUCLEAR POWER PLANTS IN UNDERGROUND INSTALLATIONS

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ENGINEERING AND DESIGN

Utilization of Nuclear Power Plants in Underground Installations and for

1. Purpose and Scope. ~~This manual is for~~ guidance in the design of underground installations and it is applicable to all elements of the Corps of Engineers having this responsibility.

~~2. General.~~ ~~This~~ The manual provides information on nuclear power to assist Corps of Engineers personnel in selecting the source of power for an underground installation that might be required to operate in a "buttoned-up" status, i.e., a completely closed and isolated situation over a period of days or weeks. The underground installation may be utilized for missile sites, command centers, communication centers, or storage facilities. Additional information and consulting services on nuclear power can be obtained from the Chief of Engineers, ATTN: ENGMC-N.

3. Sources of Power. The two general sources of power for an installation are commercial and installed generated power.

a. Commercial Power. In the consideration of possible power sources for any specific facility, particularly if located in the United States, the availability of the vast interconnected commercial public utility network is evident. However, commercial power plants and their transmission lines are vulnerable to sabotage and enemy attack and therefore not highly reliable for a military installation. In some instances the character of the power capable of delivery to the facility does not meet the stringent voltage and frequency requirements which may be imposed by special electronic equipment. While it is true that there may be long periods of standby or alert operations during which consideration could be given to the use of commercial power, it must be recognized that following an attack a hardened facility must be self-sufficient. Consequently a protected power source of sufficient capacity to insure a power supply for the critical loads must be available. If a significant portion of the electrical power demand is required for the operation of critical electronic and building service loads, the use of commercial power becomes less attractive. Several studies have been made for specific installations in which critical loads

were predominent. These studies have indicated that it is far more satisfactory, and in many cases more economical, to provide a generating plant within the installation itself to serve all the load and to eliminate any connection to a commercial power source.

b. Installed Power Generating Plant. The selection and design of a power generating plant to be installed in the protected area of the facility should take into consideration a number of factors associated with the requirement for "buttoned-up" operation. These factors include:

(1) Heat Rejection. The problem of dissipating rejected heat resulting from the thermo-dynamic cycle and mechanical inefficiencies has been a persistently difficult one to overcome. This is particularly true for the "buttoned-up" period. The rejected heat and the manner in which it manifests itself has a significant effect on the cost of the over-all utility system by virtue of its impact on the heat sink. It may be that power sources which are initially more costly can be justified on the basis of overriding costs of providing a heat disposal system. In this connection consideration should be given to the possibility that the rejected heat can be put to useful purposes.

(2) Geographic Elevation. The geographic location of the installation will determine its elevation above sea level, and this might significantly affect the performance of power sources using a fuel-air combustion cycle. For example, an unsupercharged diesel engine or an open-cycle gas turbine must be de-rated according to its elevation above sea level.

(3) Vulnerability. A power source employing a fuel-air combustion cycle must be connected with the outside atmosphere for air intake and exhaust. Connections to the surface generally involve a large expenditure, particularly in the case of deep underground facilities, and they introduce a potential weak spot in the integrity of an otherwise well-protected facility. This consideration warrants a thorough investigation of the use of power sources independent of outside air for combustion.

(4) Ruggedness. The apparent tendency toward the protection of facilities against the detonation of extremely high yield weapons brings into focus the ability of power generating equipment to withstand vibrations resulting from air-induced or ground-transmitted shock. It may be that shock isolating supports will have to be used.

(5) Compactness. High power to volume ratios are especially desirable for all underground installations. Tunneling in rock or constructing a cut and cover installation involves large expenditures, and the more compact the facility, the less expensive it is.

(6) Fuel Supply. A major problem for consideration in connection with power generating equipment is the supply and storage of fuel, particularly for use during the "buttoned-up" period. A unit's ability to utilize different types of fuel may present decided advantages. For instance, in an area where natural gas is inexpensive, it would be an economical advantage to operate the turbine with natural gas during normal operations and fuel oil, which can be readily stored, during buttoned-up periods. It is evident that a power source which does not require continuous fueling and voluminous fuel storage facilities has decided advantages in this respect; on the other hand, such a power source generally involves high initial cost.

(7) Operation and Maintenance. Power sources which are less complex and require fewer auxiliaries with a correspondingly moderate complement of spare parts, can more readily be maintained with normally competent personnel. In instances where the facility is located in a remote area, this could be a decided advantage. Obviously, a power source which is fully automatic and can operate unattended, is highly desirable.

(8) Economics. Operational, tactical and economical advantages are the most important criteria used in selecting military power generation means; whereas, economical considerations are the most important in selecting commercial generation means. In the military, overriding tactical and operational advantages in many cases justify selecting a less economical plant. It is essential that operational, tactical and economical (both initial and operating costs) factors be closely weighed in the selection and design of the power generating plant.

4. Alternative Power Generation Equipment. The above factors provide the general criteria for discussing the applicability of currently available types of power sources to underground installations. These include diesel, gas turbine, fossil fueled steam and nuclear steam plants.

a. Diesel Engine Plant. One of the most common and versatile types of power sources employs a diesel engine prime mover driving a generator. Standard commercial diesel generator units are available in a variety of sizes to the extent that singly or in multiples they could satisfy the requirements of practically all categories of hardened facilities. Although the thermal efficiency is subject to Carnot-cycle limitations, efficiencies on the order of 30% to 35% can be expected even in the smaller size plants. The engines can operate equally well using either liquid or gaseous fuels or a combination of both. Surface connections are required for combustion gases. Fortunately, a significant percentage of the cycle heat can be ejected along with the exhaust gases. However, about one-third of the heat input must be dissipated to a heat sink other than the atmosphere.

If ebullient cooling of the engine jackets is adopted, rejected heat in the form of low pressure steam can be vented to the atmosphere which would significantly reduce the load imposed on the heat sink. Table 1 presents some of the salient characteristics of a medium size diesel electric plant.

b. Open-Cycle Gas Turbine Plant. For this type of power generating equipment, two types of cycles appear to be the most applicable, namely, a simple cycle with zero regeneration and an 80% regenerative cycle. A third type of cycle utilizing a combination gas turbine-steam turbine cycle, although somewhat more efficient than the 80% regenerative cycle, is considerably more complex, which generally overrides the advantage of savings in fuel. Even with the limited range of sizes available, gas turbines can be considered adaptable to the power requirements of the majority of installations under consideration.

Cycle efficiencies of gas turbines range from 15% to 27%. The units can operate equally well on either liquid or gaseous fuel. One extremely desirable feature of the turbine cycle is that the heat rejection problem is less severe in that almost all the cycle heat, except for useful work, is ejected along with the exhaust gases. This advantage becomes less evident if heat recovery devices are found to have practicable application for heating and absorption refrigeration. The principal disadvantage of the turbine cycle is the enormous demand for air, with resulting large expenditures for surface connections and blast closures. Air induction losses and exhaust backpressures resulting from the dynamic losses of air passing through long shafts or tunnels and across blast closures may significantly de-rate the turbine. Booster fans could be used to minimize these effects, but they require additional power for operation. Another problem is the possibility of the existence of elevated air temperatures at the surface for some time after the initial shock and pressure disturbance. This elevated inlet temperature condition would apply primary to installations located near combustible areas. A sudden intake of high temperature air can cause the compressor to surge and flameout by reducing compressor speed below the minimum stable operating speed (referred speed). De-rating due to altitude of approximately 3½% for every 1,000 ft change in elevation is an inherent disadvantage of the turbine cycle and cannot be corrected by the use of superchargers as in the case for diesel engines. While turbines possess a greater power to weight and power to volume ratio than diesel engines, this factor must be evaluated against the other disadvantages, notably higher fuel consumption. (Refer to Table 1 for comparative characteristics.)

c. Fossil Fueled Steam Plant. One of the most common types of power sources for large power demands is the fossil-fueled steam plant, consisting of an oil, gas or coal-fired boilers and condensing steam turbine-generator sets. This plant is thermally less efficient than the diesel plant

TABLE 1

COMPARATIVE FEATURES OF POWER GENERATION EQUIPMENT

TYPE	THERMAL EFFICIENCY	TOTAL HEAT	COMBUSTION AIR	FUEL OIL RATE	Heat Rejection TO STACK	Heat Rejection TO HEAT SINK	Heat Rejection TO POWER PLANT AREA
Diesel Electric	35%	50.0×10^6 BTU/Hr.	1550 lbs/min. 21500 cfm	380	14.0×10^6 BTU/Hr.	14.5×10^6 BTU/Hr.	4.0×10^6 BTU/Hr.
Open Gas Turbine 80% Re-generation	25%	68.0×10^6 BTU/Hr.	7020 lbs/min. 97500 cfm	470 gph	47.0×10^6 BTU/Hr.	2.0×10^6 BTU/Hr.	2.0×10^6 BTU/Hr.
Nuclear Steam Turbine	20%	85.0×10^6 BTU/Hr.	----------	----------	----------	65.0×10^6 BTU/Hr.	3.0×10^6 BTU/Hr.
Nuclear Gas Turbine	25%	68.0×10^6 BTU/Hr.	----------	----------	----------	49.0×10^6 BTU/Hr.	2.0×10^6 BTU/Hr.

NOTE: The tabulation is based on a plant capacity of 5000 KW (net electric).

and would thus require a larger volume of fuel storage to operate a given period. However, the fossil-fueled steam plant is thermally more efficient than a nuclear plant in its present state of development, due to the use of superheated rather than saturated steam. Because of this higher efficiency the fossil-fueled steam plant requires less cooling air or water than a nuclear plant.

In common with other fossil-fueled plants, the need for combustion air and the production of exhaust gases remains a problem in a hardened underground installation. It would be possible as with a diesel plant to have closed cycle operation. The exhaust gases are voluminous, are at relatively high temperature, and contain CO_2, SO_2, as well as other contaminants. Prior to recirculation, the exhaust gases must be purified and oxygen added to support combustion. The cost of the additional equipment to allow closed cycle operation will usually raise the cost of the fossil-fueled plant above that of a nuclear plant. More detailed discussion of the various means of generating power in a hardened underground installation is contained in references 19 and 22.

d. Nuclear Power Reactors. In an underground installation, as discussed above, diesel, gas turbine and fossil fueled steam plants have the major disadvantages of requiring large,hardened,fuel storage facilities and surface connections for the intake of combustion air and the discharge of exhaust gases. Since nuclear reactors have the unique characteristics of nondependence on combustion air intake, discharge of exhaust gases, and voluminous fuel supply, nuclear power plants appear to be advantageous for use in underground installations. There are other schemes for generating electrical power which are not air-breathing, however, nuclear power is the only field tested,non-air-breathing system with sufficient electrical generating capacity to support an underground installation of the size and type envisioned. Therefore, the remainder of this manual will present the advantages, disadvantages, design criteria, and planning factors for utilizing nuclear power plants in underground installations.

5. Existing Studies. As of 1 January 1963, there are three underground installation studies which are considering nuclear power. These are briefly described in the following paragraphs.

a. PACCS Command Support Center Advanced Planning and Conceptual Design Report (reference 22) considered the following electrical generation means:

(1) Nuclear-fueled steam.

(2) Closed cycle diesel.

(3) Fossil-fueled steam.

(4) Fuel cells.

(5) Gas turbine.

(6) Thermionics.

(7) Thermoelectricity.

(8) Magnetohydrodynamics (MHD).

(9) Recycle Exhaust Gas System.

Of these nine the first two were considered the best, however, since the nuclear plant is as reliable and the cost is lower, it was recommended in lieu of the closed cycle diesel plant.

b. National Academy of Sciences (NAS) Zeus Multi-Function Array Radar (ZMAR) Study (reference 15). When this study was published there were two ZMAR utilization concepts, Urban and Hardsite Defense Systems. Both of these systems required hardened power plants; the Urban Defense System requiring a larger plant than the Hardsite Defense System. The NAS conclusion as to the power source set forth in reference 15 are as follows:

(1) For Urban and Hardsite installations, where adequate water is available for normal heat-rejection system, the nuclear-steam plant is preferred because it has no requirement for combustion air or exhaust.

(2) For Urban installations, where water supplies are so limited that evaporative cooling is necessary for heat rejection, the conventional-steam plant is preferred if underground cooling towers are used. The nuclear-steam plant becomes second choice because it requires about one-fifth of the energy for blowing air through the underground cooling tower, twice as much as is required for the conventional plant. If hardened spray ponds are feasible at these sites, the nuclear plant would be preferred because it has no requirement for combustion air.

(3) For Hardsite installations, where water supplies are so limited that evaporative cooling is necessary for heat rejection, the diesel engine is preferred. However, if hardened spray ponds are feasible, the nuclear steam plant may be a better solution.

(4) For Hardsite installations, where air cooling is required, the diesel engine plant is preferred.

(5) There does not appear to be any Urban installation where air cooling will be required.

c. Feasibility Study on the Installation of a Nuclear Power Plant in AJCC Near Fort Richie, Maryland (reference 23). The Feasibility Study concluded that the installation of nuclear plants in Army underground facilities is technical feasible. It also concluded "their reliability is at least as good as that of the presently installed diesel generators at AJCC, and they are capable of operation when isolated from the outside for at least one year". Since AJCC has a short supply of water, the study recommended operating the nuclear plant non-condensing, thus reducing the water requirement from 3500 gpm to 150 gpm. However, non-condensing operation reduces the plant thermal efficiency - in the AJCC study the design efficiency was reduced to 17.0%.

6. Advantages. The advantages of utilizing a nuclear power plant rather than a fossil fueled plant in an underground installation include the following:

a. Extended Operation Isolated From the Atmosphere. As mentioned previously a nuclear reactor requires no combustion air and produces no exhaust gases. This allows extended, completely "buttoned-up" periods. A good example of this "buttoned-up" period is the length of time the nuclear submarines can remain submerged as compared with a conventional submarine. Air intake and exhaust shafts penetrating a hardened facility must be provided with quick closing blast resistant devices which are not 100 percent reliable and therefore introduce points of weakness on what may otherwise be a relatively invulnerable facility. Hence, eliminating any of these penetrations will provide a more secure and tighter installation. Also, surface connections generally introduce large expenditures. In fact, when considering protective construction to resist blast effects from surface over-pressures in excess of 1000 psi, the design of large closures may present problems beyond the present "state of the art".

Eliminating combustion air will enhance plant reliability. A forest fire or fire storm in the area surrounding a hardened installation is likely after a nuclear strike. Either of these may cause the fossil fueled plant to reduce its power output due to high temperature combustion air or to even shutdown completely due to lack of oxygen in the combustion air. Since a nuclear plant requires no combustion air, this problem is eliminated and thus plant reliability is enhanced.

Eliminating combustion air will also reduce the possibility of radiation leaking into the installation. Since combustion air will not normally be CBR filtered, there is a good probability that shock developed by a nuclear blast may break or cause a leak in the combustion air ducts thus allowing radioactive air into the installation.

b. Complete Lack of Fuel Storage Facility Requirement. Nuclear power plants have a tremendous advantage in the volume of fuel used per unit of power produced. For example, it would take approximately 30,000,000 cubic feet of diesel fuel to produce the same amount of power that 1 cubic foot of "in place" core in a nuclear power plant could produce.

Normally a hardened installation will require an equally hardened power generation facility with sufficient fuel storage to operate the installation at least during the "buttoned-up" period plus an additional period of 15 days. This additional period will allow time to repair and restore the fuel supply system in the event of major damage. The elimination of this large hardened facility will reduce the amount of excavation required and thus reduce the initial cost of the installation. A comparison of fuel quantity required for various systems is shown in Figure 1. The storage volume of fossil fuel for a steam plant for 1 hour, 1 day, and 1 month of operation is shown in Figure 2.

c. Minimum Fuel Resupply. As stated above, compared with fossil fuels, the volume and weight of nuclear fuel required to produce a given quantity of power is exceedingly small. In fact, it is so small that the matter of fuel transportation in the case of a nuclear-fueled plant may be practically negligible. As a result, such a plant is not influenced by the location of the fuel resource or transport facilities as in the case of a fossil fueled plant. In general, nuclear power plants require refueling only once every one to four years depending on the core design. The reduction of the resupply problem reduces the plant operational cost, especially in remote areas.

d. Minimum Noise and Vibration Levels. A nuclear reactor produces no noise and vibrations; however, its auxiliaries (pumps and air compressors) do produce small amounts. The turbine-generator is not considered here since both fossil fueled and nuclear power plants have them, and they produce equal amounts of noise and vibration. When considerable vibrations are produced by equipment, for example, a diesel engine, special mountings and foundations must be provided which will allay vibrations which might be transmitted to the rack and to structures and equipment. The results of a recent study performed by the Air Force on the noise and vibrations of a 600 KW diesel in a missile launch control center indicated overall db levels in excess of 100 at the generator, and as much as 73 in the launch control officer's position. These noise levels cannot be tolerated for extended periods by humans and would be very detrimental to sensitive electronic equipment. By reducing the noise and vibration, the plant could be located closer to occupied areas and sensitive equipment, thus allowing a more compact installation which would reduce the total excavation cost.

e. Elimination of Noxious Exhaust Fumes. As discussed previously, a reactor produces no noxious exhaust fumes. This eliminates the problem

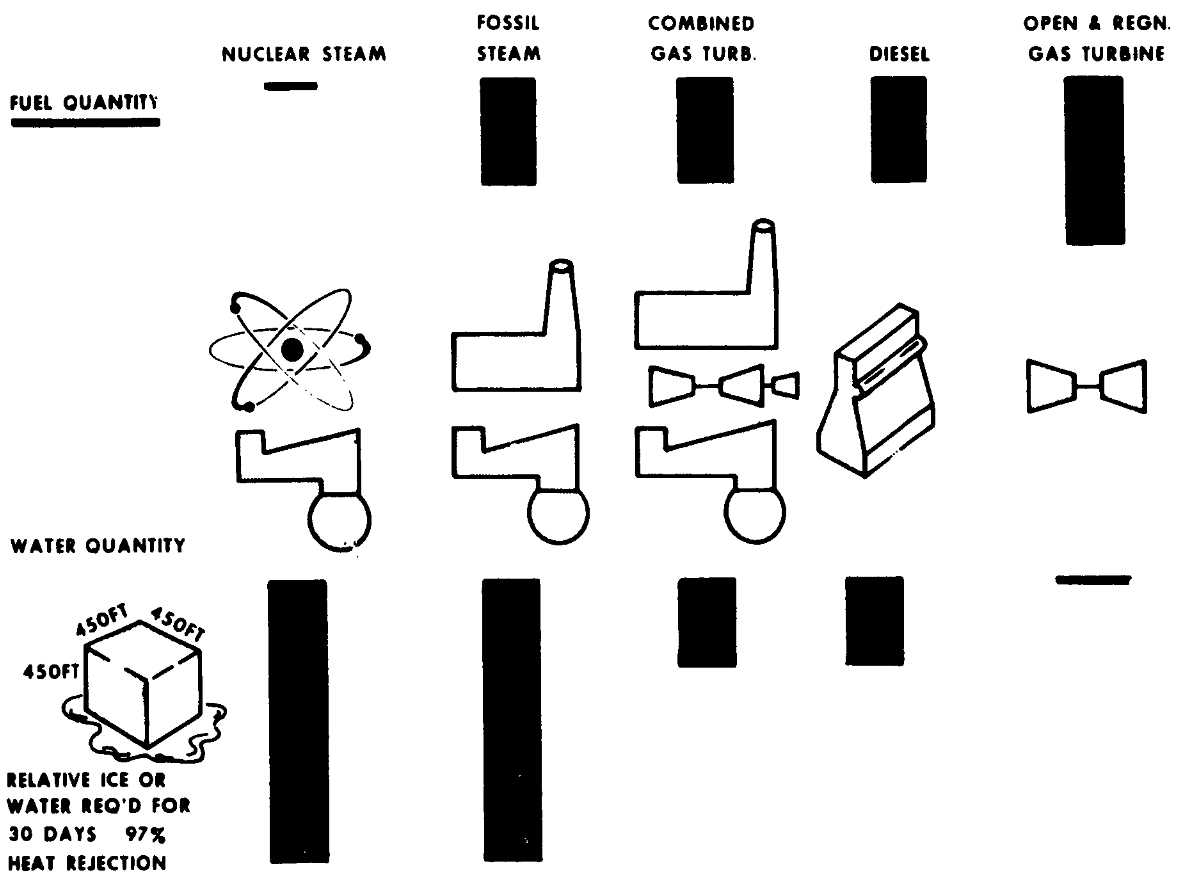


FIGURE 1

RELATIVE AMOUNTS FUEL AND WATER
100 MW PLANT

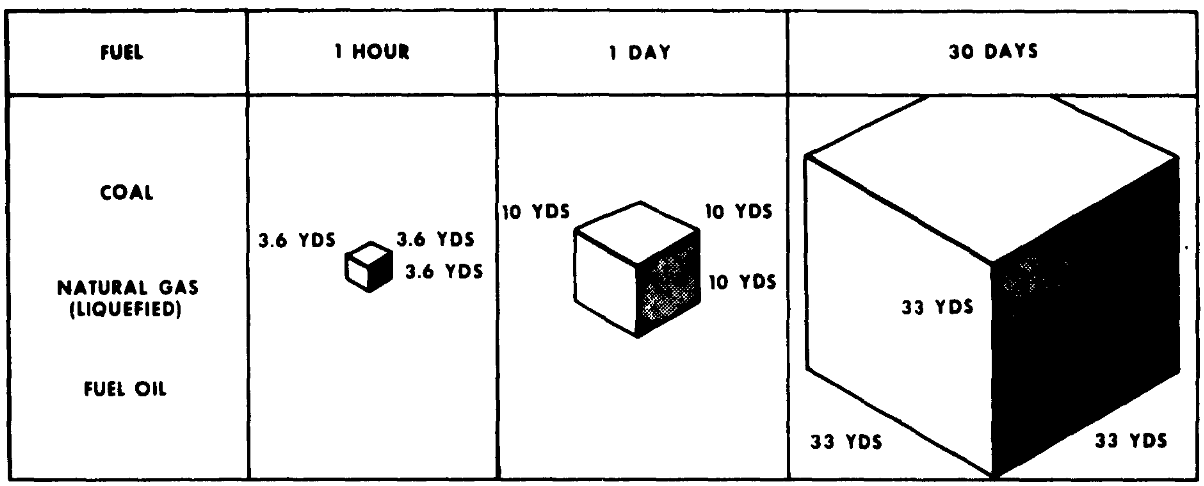


FIGURE 2

FUEL VOLUME REQUIRED FOR STORAGE

100 MW FOSSIL FIRED STEAM PLANT
PLANT HEAT RATE 11,100 BTU/KW HR

of exhausting these fumes and the danger of producing a toxic atmosphere within the installation upon operational failure of the quick closure device.

f. Inherent Ability to Follow Load. Most nuclear power plants are designed with an inherent ability to follow load without an automatic control system or the movement of manual controls. This inherent ability is due to the reactor core's negative temperature coefficient and is not found in fossil-fueled plants.

g. Reduction in National POL Demand. This advantage is not limited to military nuclear power plants, but concerns itself with all large,continuous use power plants. With the constantly increasing military requirements for POL in the field, the total demand on national petroleum resources and refining capabilities becomes a matter of real concern during wartime. Obviously, some civilian requirements will have to suffer in event of an emergency. Therefore, in selecting fuels for all large, fixed plants, it would be advisable to consider those fuels whose supply is not subject to curtailment or competition from field forces requirements.

7. Disadvantages.

a. Initial Cost. The current, but hopefully temporary, major disadvantage of nuclear power is its high initial cost. The high cost is primarily due to the following:

(1) Requirement for R&D in the design of a plant.

(2) Lack of technical, manufacturing, and operating experience.

(3) Duplication of equipment and instrumentation.

(4) Requirement for massive radiation shielding and containment.

(5) Health Physics requirements.

Examples of costs are listed in Table 2 and references 28 and 29. Unhardened nuclear power plants in CONUS become more economically competitive with fossil-fueled plants as the plant's generating capacity increases. It has been demonstrated that small (1000-2000 KW) nuclear power plants located at remote sites can produce power more economically than fossil-fueled plants due to the high cost of fossil fuel. At the present time, no duplicate nuclear power plants have been constructed in the U.S. Manufacturers have stated that the cost of the nuclear portion of a duplicated plant could be reduced as much as one-third the original cost. Several utilities companies are now designing large nuclear power plants which are expected to produce power as economically as conventional power plants. As more experience is gained on nuclear-fueled plants, the costs will eventually be reduced so that they will be able to compete economically with fossil-fueled plants throughout the world.

TABLE 2

Plant	Power	Electricity	Cost ($\$x10^6$)	Size (cu ft)	No (1) Packages	Wt (Tons)	Core Life (MW Yrs)	Type	Availability (Years) (4)	Heat Sink	Fuel/Cost(5) (mills/KWhr)	Erection Time
SM-1	10 MWt 1855 KWe net	3 phase 60 cycle 4160 volts	4.60	177,900	N/A	288(2) 2500(3)	28	PWR	2.0	Steam to river water	14.5	18 mos.
SM-1A	20.2 MWt 1650 KWe net $46x10^6$ Btu/hr (steam)	3 phase 60 cycle 2400 volts	6.67	243,100	N/A	3000(3)	28	PWR	2.0	Steam to water	10.9	18 mos.
SM-2	28 MWt 6000 KWe net	3 phase 60 cycle 4160 volts	4.26	211,680	N/A	UNK	28	PWR	2.0	Steam to water	12.6	18 mos.
PM-1	9.37 MWt 1000 KWe net $7x10^6$ Btu/hrs (steam)	3 phase 60 cycle 4160/2400 volts	3.00	33,000	16	240(2)	26	PWR	1.5	Steam to air	27.2	75 days
PM-2A	10 MWt 1560 KWe net $1x10^6$ Btu/hr (steam)	3 phase 60 cycle 4160/480 volts	4.50	60,819	27	300(2)	18	PWR	1.5	Steam to Ethyl-ene Glycol to air	19.8	78 days
PM-3A	9.36 MWt 1500 KWe net	3 phase 60 cycle 4160/2400 volts	5.25	42,700	19	450(2)	26	PWR	1.5	Steam to air	27.3	77 days
PL-1	3.6 MWt 252 KWe net $1.7x10^6$ Btu/hr	3 phase 60 cycles 4160/2400 volts	2.07	15,980	10	280(2)	30	BWR	1.2	Steam to air	20.7	60 days

Table 2 (Continued)

Plant	Power	Electricity	Cost ($\$x10^6$)	Size (cu ft)	No (1) Packages	Wt (Tons)	Core Life (MW Yrs)	Type	Availability (Years) (4)	Heat Sink	Fuel/Cost (5) (mills/KWhr)	Erection Time
PL-2	7.48 MWt 1000 KWe net $1.365x10^6$ Btu/hr	3 phase 60 cycles 4160/2400 volts	3.18	18,410	14	329(2)	30	BWR	1.2	Steam to air	15.5	50 days
MH-1A	44.6 MWt 10 MWe net @ 60 cycles	3 phase 60/50 cycles 66,44,33 or 22.9 kilovolts	11.50 (6)	374,900	N/A	UNK	112	PWR	3.0	Steam to water	6.0	30 mos.
ML-1	3.4 MWt 330 KWe net	3 phase 60 cycles 4160/2400 volts	5.50	2,978	3	38.5	1.17	GCR	First power plant (ML-1A) will be avail. during 1965.	Nitrogen to air	UNK	12 hrs

NOTES:
(1) Air transportable, less buildings.
(2) Less buildings.
(3) Including building.
(4) Time from decision to build to plant criticality.
(5) Cost of fuel cycle.
(6) Less hull, manuals and training.

b. Design and Construction Lead Time. Diesel plants have a smaller design and construction lead time than both nuclear and fossil-fueled steam plants. Lead time for nuclear plants is approaching that for fossil-fueled steam plants. In most cases the only difference in lead times of the two steam plants is the 6 to 8 weeks nuclear testing period. However, in the near future, the Army will possess standard packaged portable and mobile nuclear power plants which may reduce the nuclear plant lead time to that of diesel plants.

Lead or availability times for nuclear power plants developed in the Army Nuclear Power Program are listed in Table 2.

c. Complexity and Massiveness. In general, nuclear power plants at present are more complex than diesel and gas turbine plants. Due to the complexity and the required shielding and containment, a nuclear plant is fairly massive. Present research and development effort is geared toward reducing both the complexity and massiveness of these plants. If, however, the negligible storage volume required for nuclear fuel is compared with the large storage tanks associated with a fossil-fueled plant, then the overall nuclear plant compares favorably. See Tables 3 and 4 for a comparison.

d. Cooling Water Requirement. Power plants with the same thermal efficiencies possess identical heat sink requirements. Then depending on the plant's method of heat rejection, various quantities of cooling water or air are required. An example of this is a comparison of a gas-turbine with a nuclear plant. A gas-turbine rejects practically all of its waste heat through its exhaust to the atmosphere thus requiring no cooling water; whereas a nuclear plant can be isolated from the atmosphere and reject its heat to a water source. Therefore, if water is utilized for condensing the turbine steam, the nuclear plant will require more water than a fossil-fueled steam, diesel, or gas-turbine plant. See paragraph 13 for a more detailed discussion of heat sinks.

e. Requirement for an Auxiliary Power Source. Nuclear power plants, like any other plant, must shut down for scheduled maintenance; however, a nuclear plant also refuels during this period. While shut down, the nuclear plant will require an auxiliary source of power unless multiple nuclear plants are installed.

8. Requirements of Supported Facility.

a. General. This manual is concerned primarily with hardened underground nuclear power plants. There are unhardened underground nuclear power plants in Switzerland and Sweden. The reasons for constructing unharden underground plants were to provide natural containment in case of a nuclear accident; to alleviate real estate problems; and to provide an economical plan to heat. The Swedish plant designers do not contemplate any heating requirements after a period of two years, when the surrounding rock will have reached thermal equilibrium with the plant structure. Also, according to the designer an underground housing of this kind in Sweden is less expensive in the long ru than a building above ground. Articles on these plants are in references 3 and 4.

Table 3

Volume Data on Nuclear Plants

Plant	Elec. Output	Vol. (cu. yds x 10^3)	Cu. yds/KW
ML-1	330 KW	0.1	0.3
PL-1	380 KW	0.6*	1.6*
Kaiser's conceptual design for Pole Sta.	500 KW	13.4	26.8
Kaiser's conceptual design for Byrd Sta.	800 KW	17.1	21.4
PL-2	1.1 MW	0.7*	0.6*
PM-3A	1.5 MW	1.6*	1.1*
PM-1	1.5 MW	1.2*	0.8*
PM-2A	1.6 MW	2.2*	1.4*
SM-1	2.0 MW	6.6	3.3
SM-1A	4.0 MW	9.0	2.2
Kaiser's conceptual design for Super-Sage	5.0 MW	16.5	3.2
Kaiser's conceptual design for NORAD	6.0 MW	16.2	2.7
SM-2	6.0 MW	7.8	1.3
MH-1A	10.0 MW	13.9	1.4
Kaiser's conceptual design for Inchon	10.0 MW	19.2	1.9
Super heat reactor	17.5 MW	88.0	5.0
GE BWR	22.0 MW	10.5	0.5
GE BWR	44.0 MW	17.8	0.4

*Volume of packages only.

Table 4

VOLUME COMPARISON

	Nuclear				Diesel			
Elec Output	Vol. (Cu ydx10^3)	Cu yd/KW	Vol (cu ydx10^3) w/o fuel	Cu yd/KW w/o fuel	Vol (cu ydx10^3) 1 mo fuel	Cu yd/KW 1 mo fuel	Vol (cu ydx10^3) 14 mo fuel	Cu yd/KW 14 mo fuel
500 KW	13.4	26.8	4.9	9.8	5.8	11.6	17.7	35.4
800 KW	17.1	21.4	5.3	6.6	6.6	8.2	23.7	29.6
5 MW	16.5	3.2	9.5	1.9	18.2	3.6	131.5	26.4
6 MW	16.2	2.7	8.3	1.4	18.7	3.1	154.3	25.8
10 MW	19.2	1.9	17.0	1.7	34.4	3.4	251.0	25.1

The volume of the fuel supply was based on the 500 KW (Pole Station) and 800 KW (Byrd Station) study.

b. Levels of Protection. The mission of the underground facility will determine the level of protection required. The installation's supporting power plant should be hardened to at least the level of the installation. Nuclear power plants become more advantageous as the level of protection increases because air intake and exhaust facilities, and hardened fuel storage facilities become more costly and less feasible.

c. "Buttoned-Up" Period. The length of the "buttoned-up" period and the requirement for a restored capability, if any, will obviously affect the type of power source, water supply, heat sink and the storage of consumables. The longer the "buttoned-up" period the more advantageous is a nuclear power plant due to its ability to be non-dependent on fuel supply, on a resupply of air and on an air exhaust system. A heat sink is the major problem of a hardened nuclear-fueled plant, expecially during the "buttoned-up" period. Heat sinks are discussed in paragraph 13.

d. Recoverability. Insomuch as nuclear power plant dependence on refueling, air supply and air exhaust is nil, the recovery problem after the attack is less than a fossil-fueled power plant. Depending on the system adopted, the heat sink will probably be the major recovery problem.

9. <u>Logistical Considerations</u>.

a. Pre-Attack. It would be advisable for a hardened nuclear power plant to have an extra core on hand at all times. This would allow sufficient fuel to supply power prior, during and after an attack until a new core could be provided. Sufficient repair parts should be on hand for at least one year. Preventive maintenance must be conducted on a very high standard to insure excellent plant reliability.

b. During Attack. With a sufficiently hardened heat sink, a nuclear plant is completely independent of logistical consideration during this period barring any major component failure for which repair parts are not on hand.

c. Post-Attack. With the amount of fuel and repair parts on hand as stated in paragraph 9a and with a sufficient heat sink, the plant will be able to operate for one core life barring again any major component failure. One core will operate a plant at full power from one to four years depending on core design. Consideration must be given to the fact that after an enemy attack, the power produced within the hardened installation may be the only source of power in the area. This source could then be used to rehabilitate the area. The economics of the power produced during the pre-attack period is, in most cases, more than compensated for during and after the attack.

10. Utility Requirements of Facility.

a. Power. Since hardened underground nuclear and fossil-fueled power plants are very expensive, every effort should be made to minimize the power requirement. This can be accomplished by the following:

(1) Utilizing gas discharge type of lighting such as fluorescents.

(2) Utilizing transistorized electronic equipment.

(3) Having light color walls so as to reflect light thus conserving electricity. This may require painting the rock white or a similar color.

(4) Establishing an effective electrical conservation program within the installation.

(5) Optimumizing the equipment design to provide maximum efficiency with minimum power and heat sink requirement.

b. Heating. Both heating and air conditioning may be required in underground installations to maintain conditions within limits satisfactory for human occupancy and for preservation of equipment, supplies and materials. The air temperature in an occupied underground space is usually maintained above the initial temperature of the surrounding earth or rock. Accordingly, heat flows from the air to the earth or rock at a rate dependent on the temperature differences of air and earth or rock. With time, the nearby earth or rock is warmed, and the heat input required to maintain a given air temperature decreases. When or if the internal heat load, such as the heat liberated from personnel, lights, motors, and other equipment exceeds the rate of heat absorption by the earth or rock, the space air temperature will rise, unless the excess heat is removed by some cooling means such as ventilation air or air conditioning. A good example of this was the Swedish plant mentioned in paragraph 8a. A method of computing heat absorption of rock underground spaces is delineated in paragraph 5-32, reference 25 and Section IV, reference 26.

If heat is required, steam produced from the nuclear power plant can be utilized for space heating. This is done on the PM-1, SM-1A and PL-3. The amount of space heat supplied by these plants is listed on Table 2. Heating is a relatively simple problem in an underground installation compared to the heat removal problem (heat sink).

c. Air Conditioning. Air conditioning requirement will vary with moisture and heat removal requirement. The moisture removal problem in underground installations will vary in accordance with the amount of ground water present, the type of structure, and the humidity limits imposed by its

occupants and equipment. The cooling problem depends on the type and location of the heat sink, the heat load within the installation and the outside atmospheric condition. The refrigeration cycle of an air conditioning unit requires a considerable amount of power. Minimum power would be required if the refrigeration heat sink could be maintained at a minimum temperature. However, since the heat sink is critical in a hardened installation, every effort should be taken to utilize it efficiently; and the larger the raise in the heat sink temperature the more efficiently it is used. Therefore, the final selection of the refrigeration cycle might be largely dependent upon obtaining a combination of power generation and refrigeration equipment which will produce the lowest total heat rejection with the view toward reducing to a minimum the heat sink requirement. The possibility of air conditioning through direct use of steam and without conversion to electrical or mechanical energy should be considered. Detailed material on air conditioning of underground installations is contained in reference 25 and 26.

11. Character of Connected Power Loads.

a. Technical Characteristics. A nuclear plant can produce precise power. If the power demand of an installation increases very rapidly, a boiling water reactor can produce the required amount of steam quicker than conventional steam boilers. At the present time a considerable amount of work is being done to improve the nuclear plant's capability to produce precise power.

b. Reliability. The key element in predicting system reliability is the availability and reliability of the units which make up the system. For nuclear power plants the achievable availability and reliability are difficult to predict since relatively few units are operating and a majority of these have had substantial research and development objectives in addition to power generation. However, recent operation of water reactor power plants, such as Yankee, Dresden, and PM-2A, has shown that, making allowances for difficulties during the initial period of break-in operations, the availability of a nuclear power plant unit should be comparable with that of a conventional steam power plant, with the exception of the additional planned outages required in nuclear plants for periodic refueling. For example, during 17 months of operation on Yankee's first core, the reactor was at operating temperature and pressure, ready to deliver steam, 96% of the time. Overall plant load factor, about 70%, was lower because of mechanical troubles in the secondary plant and shutdowns for testing required by license. In the first half of 1962 Dresden made a six-month run in which net generation was 683,150,400 KWh, capacity factor was 87.4%, availability 91.2%; from July 1 to shutdown, average capacity factor was 91.5%, availability 96%. The Army Nuclear Power Program's oldest field plant, PM-2A, had an availability of 95% during CY 1962. Since the availability of a base loaded conventional steam power plant is about 95%, the availability of a base loaded (80% plant operating factor) nuclear power plant would be approximately 93% (allowing one additional week per year of

planned outage for refueling). Typically this availability would be derived from: forced outages - 2% of operating hours, maintenance outage - 3% of operating hours, extra planned outage for refueling - 2% of operating hours. Hence, by utilizing multiple units, high reliability from nuclear power plants can be obtained.

12. Site Characteristics.

a. Location. In many cases, such as missile sites, the site will be selected to optimize the installations mission and relatively little priority is given to optimize for power generation. However, the desirable site characteristics for a nuclear power plant are similar to a fossil-fueled plant. The major difference is that since a nuclear plant is, essentially, non-dependent on fuel transportation, the location of the plant is not influenced by the location of the fuel resources or transport facilities.

The utilization of existing openings, such as mines or caves, in the area of consideration may be advantageous when they are sufficiently stable and readily adaptable to the requirements of the installation. Although caution should be exercised in such cases, large savings may be realized in the normally high excavation costs.

Site characteristics for underground installations are discussed in reference 24.

b. Geology. The geologic characteristics for an underground nuclear power plant are the same as for a fossil-fueled power plant and are discussed in reference 24. In general, the geologic characteristics of a site to look for are rock formations which are easily excavated, but should also be structurally stable at sufficient depth below the surface to provide adequate protective cover. It is important to point out these geologic factors which contribute to the stability of underground openings, as well as the factors which contribute to their instability, such as faults, joints, bedding planes, cleavage, etc. There are also certain factors other than structure, such as depth and occurrence of ground water, which have an important bearing upon the desirability of a given site. Paragraph 21c discusses briefly the geology of a site in reference to its containment characteristics.

c. Hydrograph. A preferred condition would be a site located close to a river or lake which would supply the water necessary for cooling purposes in reactor operation. If sufficient water supply cannot be obtained from lake and river water, or subsurface wells, it will be necessary to provide air cooling facilities.

In considering the adequacy of a source of water, the minimum flow of stream or extreme low level of a lake is assumed a determining factor. On the other hand, sites above maximum flood level should be selected.

Although specified water quality may not be available without treatment, such treatment should be economically feasible. In connection with the utilization of lake or river water for reactor cooling purposes, it will be necessary to obtain approval for what may be termed pollution to the water, such as raising slightly the temperature of the water and possibly some slight radiological contamination. Both actions may have injurious effect on both fish and plant life in the water.

The possibility of ground water (and subsequent water supply) contamination in case of a reactor incident must be investigated. A suitable lining of the excavation should help prevent seepage, although there is no certainty that tiny cracks might have opened up by the explosion allowing some contaminated seepage. In any case, it is deemed advisable to confer with the Ground Water Branch of the U.S. Geological Survey when considering a particular site for an underground installation. If it is known that extensive seepage takes place, eventually leading into known water supply, the site should be rejected.

13. Heat Sinks.

Power plants, whether they are nuclear or fossil-fueled, with the same thermal efficiencies have the identical heat sink requirement. However, the required type of heat sink may differ in accordance with the power source. A diesel engine rejects approximately 1/3 of its heat to the atmosphere thru its combustion exhaust gases, 1/3 to cooling water, and 1/3 to the electrical generation process. The gas turbine rejects practically all the cycle heat, except for the useful work, as exhaust gases. Since a nuclear reactor produces no exhaust gases, heat sink type and size will be different from that of a fossil-fueled plant. For example, if hardened cooling towers are utilized as a heat sink, the nuclear plant will require approximately twice the capacity required by a diesel plant. Therefore, the nuclear plant's advantage of requiring no combustion air intake or waste gas exhaust facilities is compensated to some extent by requiring a larger heat sink (i.e., cooling tower, etc.). Whether a nuclear or fossil-fueled power plant's heat sink is the more expensive is not obvious since the elaborate hardened intake and exhaust structures must be considered as a portion of the fossil-fueled power plant's heat sink.

Operating procedures and employment of certain auxiliaries basically altering the temperature level of the heat rejection process could minimize heat sink requirements but at some sacrifice of plant efficiency. In view of the possibility of being cut off from outside facilities for heat disposal, an adequate hardened heat sink is required within a military underground installation for use, at least, during an emergency period. As considered herein, a heat sink may be defined as a body of high thermal capacity relative to the rate at which heat is transferred to it.

In addition to the power plant heat rejection requirement, the heat sink must also dissipate the heat given off by the facility's electronic equipment. This will vary in accordance with the installation's mission and can be a considerable amount. Nevertheless, it will be the same amount for all types of power generation means and thus requires no further discussion in this manual.

There are various methods and combination of methods available to be utilized as heat sinks. Selection of the method will depend on the installation and site selection. The following paragraphs discuss briefly some heat sink concepts and indicate references where additional information can be found. Table 5 lists the advantages and disadvantages for various heat sinks.

a. Once Through Cooling. This is an economical and efficient method but requires a large body of cold water. A river, lake, underground aquifer or reservoir may be utilized. Figure 1 compares the required amount of water required for various power generation means. See paragraph 13c, below, and references 13 and 17.

b. Rock or Earth. The rock or earth surrounding an underground facility is a natural heat sink which has some capacity for heat absorption. Pipes, drill holes, or tunnels may be used to transport the water throughout the rock. Long lengths of water passages will be required to provide sufficient heat transfer area. This complex of passages is susceptible to differential earth movement from a nuclear blast's earth shock. By far, the best feature of this sink is that it requires no water except for the small amount required for make up due to leakage. If a small underground water source is available, no breach of the surface is required. See reference 19 and 26.

c. Underground Reservoirs. All underground reservoirs, whether they consist of water, ice, or a chemical, have the distinct advantage of not requiring any breaches to the surface. They are, however, limited in the time of operation since the reservoir will eventually become too hot for efficient condensing purposes. If water is utilized, precooling the reservoir would provide a greater heat absorption capability but require more equipment. Larger heat absorption capability than a water reservoir possesses can be obtained by using an ice-water combination, ice, or a chemical substance. See reference 16, 17, 18, and 19.

d. Cooling Towers. The atmosphere itself provides a heat sink of unlimited capacity, and therefore should be considered in selecting a heat sink for a hardened facility. However, the temperature of the atmosphere has a large effect on the capacity of a plant which uses the atmosphere as a heat sink. When studying cooling tower feasibility, consideration should be

Table 5

Advantages and Disadvantages of Various Types of Heat Sinks

ADVANTAGES:	DISADVANTAGES:
1. Once Through Cooling:	
1. Minimum mech. equip. req'd.	1. Large body of cold water req'd.
2. Temp of cold water not affected significantly by weather variation.	2. Inlet and outlet structure requires hardening.
3. Unlimited supply eliminates or minimizes need for hardened storage reservoirs.	3. Tides and wind sometime affect water level at intake.
2. Rock or Earth	
1. Very little makeup water req'd.	1. Vulnerable to differential earth movement thus cutting water passages.
2. Temperature of cold water not affected by weather variation.	2. Excavation of passages or drilled pipes are very costly.
	3. Known technology is very limited.
	4. Suffers from steadily decreasing efficiency as the rock or earth temperature rises.
3. Underground Water Reservoir	
1. Simplest system available.	1. Requires large excavation volumes.
2. Minimum mech equip req'd.	2. Suffers from steadily decreasing efficiency as water temperature rises.
3. Temperature of cold water not affected by weather variations.	3. Vulnerable to rupture from earth shock.
4. Require no breach in surface.	
4. Underground Water Ice Reservoir	
1. Same as underground water reservoir.	1. Same as underground water reservoir.
2. Higher heat absorption capability than water.	2. No feasible reliable method has yet been devised for the distribution of manufactured ice in large reservoirs.
3. Smaller volume reservoir req'd.	3. Problem of maintaining ice content in the reservoir after it has been filled not solved yet.
4. Excavation cost is less.	4. Mechanical equip req'd to store and maintain the ice is very costly.

ADVANTAGES:	DISADVANTAGES:
5. Underground Chemical Reservoirs	
1. Possess highest heat absorbing capacities per unit volume.	1. High cost of chemical.
2. Smallest volume reservoir req'd.	2. The higher temperatures produces lower operating efficiency.
3. Excavation cost is at minimum.	3. Suffers from steadily decreasing effeciency as chemical's temperature rises.
4. Require no breach in surface.	
6. Above Ground Spray Pond Cooling with Hardened Reservoir	
1. Low pumping head.	1. Total loss of pond water during blast.
2. Lowest maintenance & operating cost.	2. Contamination of pond with fallout debris.
	3. Hardened reservoir req'd to maintain water flow to condenser.
	4. Distribution piping exposed to blast.
	5. Large area req'd.
	6. Makeup water Q-high.
	7. Dependence on wind velocity for efficiency.
	8. Drift nuisance.
	9. Large area oriented to prevailing winds.
	10. Extension supply piping & collection system req'd.
7. Cooling Tower	
1. Independence of wind.	1. Considerable operating & maintenance required.
2. Minimum drift loss.	2. Open exposure to blast forces.
3. Orientation flexibility.	
4. Integral storage reservoir.	
5. Fewer doors & covers.	

ADVANTAGES:	DISADVANTAGES:
8. <u>Fin-Fan Cooler</u>	
1. Minimum water makeup quantity req'd.	1. Highest capital cost.
2. Low blast exposure.	2. High maintenance.
3. Minimum reservoir capacity req'd.	3. Cooling tower unit req'd for service water.
	4. High operating cost (HP) req'd very high).
	5. Subject to ambient weather variations.
	6. Requires prototype to determine configuration vs. recirculation effect.

given to the open filled type, the closed prime surface evaporative type, and the close extended surface dry type (fin fan cooler). All of these are extremely vulnerable to blast pressures and therefore must be hardened if they are required to operate after the blast pressures subside. References (17) and (25) discuss these in more detail and reference (13) contains a few conceptual designs.

e. Spray Ponds. A spray pond can be designed with some degree of hardness. On the other hand, a spray pond is far less efficient than any type of cooling tower. See reference (17) for a more detailed discussion and reference (13) for a conceptual design.

14. Projected Facility Life. The designation system for nuclear power plants in the Army Nuclear Power Program is described in paragraph 15. The type of plant chosen for an underground installation will depend on the projected facility life. For example, if utilization of an installation is contemplated for the life time of the nuclear power plant, a stationary type of plant would be selected. However, if the installation is planned to be utilized for a shorter period of time, a portable or mobile type of plant would probably be chosen.

15. Army Nuclear Power Program (ANPP) Plant Designation. Nuclear power plants in the ANPP are classified by mobility and power level. The designation consist of two letters, an arabic number and a possible capital letter following the number.

a. First Letter - Degree of mobility:

S - Stationary - Permanent construction; not designed for subsequent relocation.

P - Portable - Prepackaged at the factory for transportability and rapid assembly at site.

M - Mobile - Can be moved intact, or virtually intact; may or may not operate in transit.

b. Second Letter - Power Range:

L - Low 100-1000 KWe.

M - Medium 1000-10,000 KWe.

H - High 10,000 KWe or higher.

c. Arabic Numeral - Order of initiation of projects with the same tw letter designation.

d. Capital Letter Following Arabic Numeral - order of initiation of field plants of a specific type. Absence of final letter indicates prototype or pilot model.

16. General Description of Plants Currently Available (as of March 1962. Reference (27) lists all the nuclear reactors built, being built, or planned in the United States. There are too numerous nuclear power plants in existence to describe them all, so only ANPP plants will briefly be discussed. In January 1963, ANPP had 5 plants in operation (SM-1, SM-1A, PM-1, PM-2A and PM-3A), 1 in design stage (inland Antarctica plant), 1 under construction (MH-1A), 3 designs completed with no actual DOD requirement for the plant (SM-2, PL-1 and PL-2), and 1 in testing stage (ML-1). Table 2 contains some of the technical data of these plants.

a. The SM-1 was constructed as a prototype. It is an Army reactor and has been in operation since April 1957 at Fort Belvoir, Va. The primary purpose of this plant is to train all Army, Navy, and Air Force nuclear power plant operators. Its secondary mission is to perform R&D and to produce power. When producing power, the plant can be placed in parallel with Virginia Electric Power Company.

b. The SM-1A went critical in March 1962 and is furnishing Fort Greely, Alaska station electrical power and steam heat. This plant is quite similar to the SM-1 except for total power output (about double) and vapor containment. The SM-1A utilizes the "pressure suppression" type of vapor containment, with an inner shell to absorb the energy release in case of an accident, and a vapor tight outer shell to prevent the spread of radioactive debris. This is an Army reactor.

c. The SM-2 was designed to support Nike Zeus System. The requirement never materialized; therefore, the plant was not constructed. The plant is presently an "on-the-shelf" design waiting a mission.

d. The PM-1 is the prototype of the portable-medium power reactor. This plant went critical in February 1962 and is the Air Force's first nuclear power plant. It is providing electrical power and steam heat for a radar station at Sundance, Wyoming.

e. The PM-2A was constructed by the Army in 1960 at Camp Century, Greenland. Camp Century is located on the icecap 138 miles from Thule, Greenland and supports arctic research by the U.S. Army Polar Research and Development Center (PR&DC). Housed, as is the rest of the camp, in cut and cover snow tunnels the plant provides electrical power and heat for this subsurface operation. The plant consists of 27 air transportable modules to facilities movement and to minimize on site construction effort.

f. The PM-3A is the first U.S. Navy land based nuclear power plant. Construction commenced at McMurdo Sound, Antarctica in December 1961 and the plant went critical in March 1962. This plant also consisted of air transportable packages (19) to allow rapid on-site construction time (77 days).

g. PL-1 and 2 are "on-the-shelf" designs and both are boiling water reactors. Both plants were planned to supply power for remote locations. Construction is pending firm DOD requirement.

h. The MH-1A is ANPP's first reactor design to produce 10,000 KWe or more and the first to be constructed on the hull of a ship. Design was completed in 1962 and construction commenced in January 1963. This Army plant will travel throughout the whole world during peace or war-time producing power where needed the most.

i. The ML-1 is being designed and tested and is the first mobile nuclear power plant. It will be mounted on a standard "low-boy" trailer and utilized by the Field Army. It is also ANPP's first gas cooled reactor. Field plant delivery is scheduled for 1965.

17. <u>Plants to Be Available in Time Frame 1965-1970 (No Major Technological Breakthroughs)</u>.

a. The present pressurized and boiling water reactor technology will advance so that the following improvement can be expected during the 1965-1970 period.

(1) Specific Volume Reduced. The volume of the plant per kilowatt will be reduced substantially.

(2) Core Life Time Increased. By 1965 core life time will be about 250% longer than the cores used during 1957-1964 period.

(3) Lower Fuel Cost. Due to higher percentage burnup, less frequent fabrication and more economical fabrication methods, the fuel cycle cost has been reduced and will be further reduced in the future.

(4) Reliability Increased. Thru improved fabrication techniques and quality control, reliability will be increased.

(5) Reduced Plant Duplication. Thru improved technology and experience, duplication of equipment and instrumentation will be reduced.

(6) Increased Transportability. With the reduction in specific volumes and plant duplication, the plants will become more transportable.

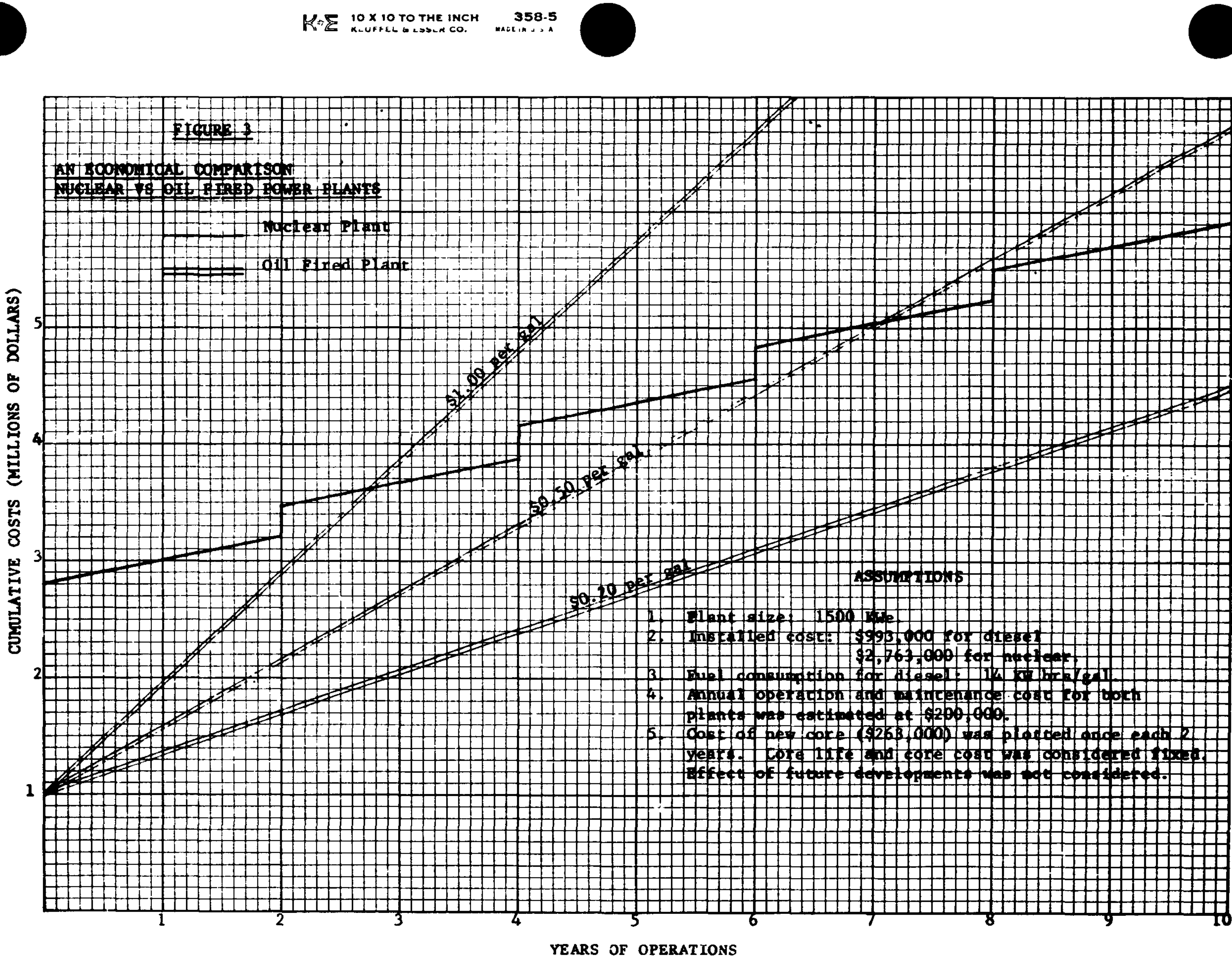
(7) Initial Cost Reduction. With the reduction of the specific volume and plant duplication and the general improvement in the state of the art, initial cost will be reduced by at least 50%.

b. Size of nuclear power plants will be reduced significantly as a result of the Military Compact Reactor (MCR) Program. Several liquid metal cooled MCRs will come into existence during the 1965-1970 period. During the early part of this period a 2000-3000 KWe power plant weighing less than an equivalent size diesel plant will be available. Later during this period, 3 to 10 MWe mobile plants will be developed. The decrease in size and weight of the MCRs compared to the existing Boiling Water Reactors (BWR) and Pressurized Water Reactors (PWR) plants will greatly increase nuclear power plants' transportability.

18. Economic Considerations. It is necessary, when designing, to consider the costs of the installation to meet the two vastly different operating conditions - normal and "buttoned-up". The system should not be designed primary to meet one condition as economically as possible and then be adopted to meet the second operating condition. At the same time, the installation should be designed with the possibility and in fact probability of future expansion of the facility.

As pointed out before, power presently produced by nuclear power plants in the continental United States is more expensive than that produced by fossil-fueled plants. In the military, mission is the foremost consideration and economy is secondary; therefore, the operational and logistical advantages discussed in paragraph 6 may justify the higher costs. An economical comparison between nuclear and fossil fuel power plants is in Figure 3. The variable shown here which determines whether a cost cross over point exists, is the cost of fuel. It is therefore obvious, that the present small nuclear power plants can be more economical than fossil fuel plants in remote areas.

a. Initial Costs. The initial costs for nuclear power plants will continue to be reduced and thus approach fossil-fueled plant costs, but for the foreseeable future the cost of small nuclear power plants will not be reduced below fossil-fueled plants. Installation of a nuclear plant underground reduces the normal requirement for man made reactor shielding and containment (see paragraph 21). This requirement reduction will lower the cost of the plant, thus compensating for the higher cost of a hardened facility and a nuclear plant. This was demonstrated in a General Electric study (reference 5) which showed that the structural cost for an unhardened


K+E 10 X 10 TO THE INCH 358-5
KEUFFEL & ESSER CO.
FIGURE 3
AN ECONOMICAL COMPARISON
NUCLEAR VS OIL FIRED POWER PLANTS
Nuclear Plant
Oil Fired Plant
$1.00 per gal
$0.50 per gal
$0.20 per gal
ASSUMPTIONS
1. Plant size: 1500 KWe.
2. Installed cost: $993,000 for diesel
$2,763,000 for nuclear.
3. Fuel consumption for diesel: 14 KW hrs/gal.
4. Annual operation and maintenance cost for both plants was estimated at $200,000.
5. Cost of new core ($263,000) was plotted once each 2 years. Core life and core cost was considered fixed. Effect of future developments was not considered.
CUMULATIVE COSTS (MILLIONS OF DOLLARS)
1
2
3
4
5
1
2
3
4
5
6
7
8
9
10
YEARS OF OPERATIONS

nuclear plant is at least twice the cost for the other plants considered (paragraph 18 c). However, the study indicated the structural costs for a hardened power plant were nearly independent of plant type. This was to be expected because a portion of the additional structure required for hardening is already provided in the unhardened plant for shielding.

ANPP second generation nuclear power plant primary goal is the reduction of the initial plant cost by 50%. Attainment of this goal at this time is quite promising. These plants will be available by 1970.

b. Operating Costs. Since initial cost for nuclear plants is high, the fixed charges on construction cost is also higher than fossil-fueled plants. Fuel cost is the major factor which will allow a nuclear plant to produce power more economically than a fossil-fueled plant. Fossil fuel cost will vary with location and quantity used, whereas, nuclear fuel cost is practically independent of these. The cost of operation and maintenance will depend on the type of nuclear power plant and on the design and and arrangement of the equipment, especially as these affect the ease and speed with which maintenance and refueling operations can be performed. However, in general, operation and maintenance cost, less interest on loan, will be approximately the same for nuclear and fossil fueled plants. Operation and maintenance cost should decrease as operating experience is gained.

c. Total Cost of Power. In a recent study made by the General Electric Company for a hardened radar installation, an economical comparison was made of the following types and sizes of power plants:

(1) Nuclear (4-37.5 MWe units).

(2) Regenerative cycle gas turbine (RC-GT). (5-27 MWe units).

(3) Simple cycle gas turbine (light weight) (11-9.375 MWe units).

(4) Simple cycle gas turbine (industrial) (9-12.5 MWe units).

(5) Gas-steam turbine (STAG)(7-19.2 MWe units).

(6) Fossil fuel steam (5-25 MWe units).

Results of this study showed that a nuclear plant would generate power over a 20 year period throughout CONUS except for the South and Southwest cheaper than the other means. Natural gas is cheaper in the South and Southwest thus allowing STAG, RC-GT and fossil fuel steam plants to produce power slightly (less than 2%) cheaper than a nuclear plant.

References 28 and 29 discuss in more detail costs of nuclear power plants.

19. Scheduling Consideration.

a. Design Lead Time: As discussed in paragraph 7b, the design lead time for a large nuclear plant is similar to that of a fossil fueled plant. However, when small (less than 8000 KW) plants are considered, there are fossil fueled plants which require relatively little lead time as compared to that required for nuclear plants.

b. Construction (or installation) lead time. Installation of small nuclear plants will take longer than equivalent fossil fueled plants; however, installation of large fossil fueled and nuclear plants are approximately the same.

20. Physical Characteristics.

a. Space Requirements. The volume required per unit of power has been reduced in the past few years,and it is anticipated to be reduced considerably more in the future. When equipment is to be installed underground and mounted to withstand high shock loading, minimum size and weight are the utmost importance. Table 3 shows a comparison of specific volume (cubic yards/KW) of some nuclear power plants.

b. Layout. Layout of a nuclear power plant is somewhat similar to that of a steam turbine plant. The major difference is that the boiler and fuel handling equipment is replaced by a reactor and containment vessel. A boiling water reactor, in addition, also takes the place of the steam generator.

21. Requirements Unique to Nuclear Power Plants.

a. Shielding. Due to the high intensity radiation produced by a nuclear reactor, large masses of radiation shielding are required. Shielding surrounds the reactor core and can consist of concrete, steel, water, rock, earth, or similar materials and combinations thereof. The shielding problem in an underground installation is not as critical because of the availability of the surrounding earth or rock. Plant layout can minimize or completely eliminate the requirement for man made shielding requirements. Above ground nuclear power plants are in general heavier than fossil fueled plants, and this extra weight consists mostly of shielding. Elimination of some or all of the man made shielding will reduce the cost of a nuclear power plant substantially.

b. Psychological Aspects. There are two psychological aspects of underground nuclear power plants. That is, the fact that installation

is underground, and the fact that it is a nuclear power plant. Psychological aspects of underground plants in general are not within the scope of this manual, however, discussion of this topic is contained in reference (24). The presence of a nuclear reactor in a compact installation might make some people fearful. This affect is caused by lack of knowledge and the belief that a nuclear reactor is a potential nuclear bomb. Only through training can this fear be overcome. Instill in the occupants the knowledge that a nuclear reactor is safe and that a nuclear explosion from a reactor core is impossible due to its small mass and lattice configuration.

c. Containment Against A Reactor Incident. According to the best judgment of experts in the reactor field, the likelihood of a major reactor accident is, fortunately, extremely small. Nevertheless, the possibility exists that through highly unlikely combinations of mechanical and human failures such an incident may occur. The principal element of danger to the general public in nearby areas is the possibility of radiation exposure and contamination, if the fission products in the reactor should be released.

Basic requirements for the design of a containment vessel must take into consideration system failures or reactor incidents even though their probability of occurrence may be minute. The containment structure, whether built aboveground or underground, must be designed to withstand, without rupture, all shock waves, missiles, increases in temperature, and increases or decreases in pressure resulting from these occurrences. Possible events which might effect the container are included in the following categories:

(1) Nuclear Incidents. Nuclear Power reactors do not have high concentrations of fuel nor the triggering mechanisms as found in nuclear weapons, and do not present anything like the hazard expected in a nuclear explosion. Actually, the physical damage resulting from the worst accident at an ANPP reactor would roughly approximate the damage caused by a TNT charge weighing about 50 pounds.

(2) Non-Nuclear Reactions. Power reactors, are designed to operate at high pressures, contained by the reactor vessel and coolant systems. The energy stored in these systems is considerable for large reactors. In the event of a rupture in these reactor systems, the containment vessels would be required to withstand the shock waves and pressure increases released by the stored energy. Other possible non-nuclear accidents include sodium water reactions and possible reactions between water coolants and some fuel element cladding materials.

(3) Coolant System Failures. A major piping failure in a power reactor system using water as the coolant, such as in a boiling water reactor system, would result in the superheated water in the system flashing into steam as it escapes inside the containment vessel. The design

of the containment vessel then involves determination of a volume sufficiently large to permit containment at a reasonable pressure, and an economic determination can be made of optimum vessel size above the minimum as required for functional use.

Special provisions may sometimes be made to prevent damage to the container shell by flying missiles resulting from such accidents as reactor turbine or pipe rupture.

(4) Missiles and Forces of External Origin. A conventional type containment must be designed to withstand high winds, earthquakes, etc. In addition, it can be imagined that missiles of external origin, such as crashing aircraft and, of course, enemy weapons, might rupture the above-ground containment shell, then damage part of the reactor system releasing radioactive materials. In regard to protection from this occurrence, the underground scheme is by far superior to the thin-skinned steel container of the above-ground scheme.

An underground installation in rock is expected to give an almost perfect protection against any internal excursion, as well as superior protection against any external forces. As far as structural strength is concerned there is ample inherent strength in the rock cover plus a solid rock lining, to resist an interior explosion of any reasonable magnitude, involving blast and missiles as well as high temperatures. There remains the possibility of contamination of underground water supplies through opening up of tiny cracks in the rock lining by the explosion and subsequent contaminated seepage into the rock. A suitable concrete lining supplemented by a light-gaged metal lining for the lower, or bottom part of the reactor building (where contaminated water is likely to collect), would give the required protection. Of course, sites with very rapid water seepage may be excluded from consideration altogether, because of the contamination possiblity as well as associated excavation difficulties.

It is suggested that the U.S. Geological Survey (Ground Water Branch, Water Resources Division) be requested to examine each proposed location to determine the ground water conditions. They would have the necessary data at hand and experience in pointing out possible problems and difficulties which may be encountered. Possibly, even steam under pressure could penetrate into the rock causing some contamination of the surroundings.

The question of how deep it would be necessary to go to get down into dry rock, cannot be answered directly. In most cases the dry igneous rock would be down several thousand feet, generally impractical for consideration.

A shale formation would be the better geological formation as far as retaining contaminated fluid is concerned; structurally, however, shale would be less desirable. Sandstone and, to some extent, limestone formations have too many cracks and fissures to meet the requirements and would in all probability need a good, tight lining.

The cost of containment features constitute a considerable portion of the total cost of an installation. Studies show that containment varies from approximately 8-17 percent of the total construction cost. Therefore, by constructing a plant underground, containment costs can be reduced considerably.

d. Radioactive Waste. A nuclear power plant produces radioactive waste which must be disposed of by controlled and authorized means. This waste is produced in all 3 states of matter, i.e., solid, liquid and gaseous. Disposal of radioactive waste is no major problem and requires only a little more effort and control on the part of plant supervisory and operating personnel. Solid wastes must be removed from the site for disposal, however, liquid waste will normally be deposited in a nearby river. If all the liquid waste cannot be dumped into a nearby river, the waste can be reduced by evaporation to a smaller volume of more highly radioactive liquid. This liquid can then be removed from the site for disposal. Gaseous waste is normally small and can be exhausted to the atmosphere.

FOR THE CHIEF OF ENGINEERS:

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1 Appendix
Bibliography

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APPENDIX I

BIBLIOGRAPHY

1. Bechtel Corporation, Base Power Supply Study, for U. S. Air Force Ballistic Missile Division, Los Angeles, California, Dec 1959.

2. Beck, Christian, "Engineering Study on Underground Construction of Nuclear Power Reactors." United States Atomic Energy Commission, AECU-3779, 15 Apr 1958.

3. De Haller, P. and A. F. Fritzche, "Sulzer project for a prototype heavy water power reactor for location in an underground cavern," Second International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958, Proceedings, vol. 9, P/246, pp. 16-35. (U.N. Doc. A/CONF.15/1 Eng. V.9).

4. Fritzsche, A.F. and deHaller, P., "Project for Nuclear Heating and Power Plant of 30,000 KW Thermal Output," Sulzer Tech. Rev. V40 n3 1958 p5-14.

5. General Electric Company, Marine & Defense Facilities, Wash., D.C., Electric Power for ZMAR, April 12, 1962 (SECRET).

6. Industrial Systems, Westinghouse Electric Corporation, ZMAR Power Systems, Presentation to National Academy of Sciences, April 11, 1962 (SECRET).

7. Inglis, D.R. and Ringo, G.R., "Underground Construction of Power Reactors" Argonne National Lab, ANL-5652, Jan 1957.

8. Kaiser Engineers, Study of Remote Military Power Applications, Report 1, Summary, for United States Atomic Energy Commission, NYOO, NYO-2937, Jan 1960.

9. Kaiser Engineers, Study of Remote Military Power Applications, Report 5, NORAD, for United States Atomic Energy Commission, NYOO, NYO-2941, Jan 1960.

10. Kaiser Engineers, Study of Remote Military Power Applications, Report 7, Super Sage, for U.S. Atomic Energy Commission, NYOO, NYO-2943, Jan 1960.

11. Kaiser Engineers, Study of Remote Military Power Applications, Byrd Station, Antarctica, for U. S. Atomic Energy Commission, NYOO, NYO-9052, May 1960.

12. Kaiser Engineers, Study of Remote Military Power Applications, Pole Station, Antarctica, for U. S. Atomic Energy Commission, NYOO, NYO-9053, May 1960.

13. Kaiser Engineers, Study of Military Power Applications. 100 MWe Nuclear Power Plant - ZMAR-X, for United States Atomic Energy Commission, NYOO, NYO-10060, Jan 1962, (SECRET).

14. Medici, M., "Problemi inerenti all' ubicazione in caverna delle centraili termoelettriche a combustible nuclare." Termotecnica V12 n2, Feb 1958, p 73-7.

15. National Academy of Sciences - National Research Council, Power Generating Systems for the Zeus Multi-Function Array Radar, September 1962 (Confidential).

16. National Bureau of Standards, "Some Observations on the Use of Underground Reservoirs as Heat Sinks." Report 4795, July 1956.

17. Newmark, Hansen and Associates, Protective Construction Review Guide (Hardening). Department of Defense, Asst Sec for Installations and Logistics, Volume 1, June 1961.

18. Parsons, Brinkerhoff, Quade and Douglas, Icing of Underground Reservoirs. Feasibility Study, Project DOD-55-VAR for the U.S. Corps of Engineers, Feb 1958 (SECRET).

19. Rand Corporation, Proceedings of the Second Protective Construction Symposium (Deep Underground Construction). Vol I & II, for U.S. Air Force, R-341, March 1959 or "Protective Construction in a Nuclear Age", Vol I & II by J. J. O'Sullivan, The MacMillian Co, New York, 1961.

20. U.S. Air Force, Conceptual Design, Nuclear Power Plant for A Superhard Facility, by Standards and Criteria Branch, Engineering Division, Directorate of Civil Engineering, June 1961 (Confidential).

21. U.S. Air Force, Rome Air Development Center, Air Research and Development Command, "General Design Criteria for USAF Nuclear Power Plant Applications," by Gilbert Associates, Inc., GAI Report No. 1499, RADC-TR-59-132, June 1959, (Astia No. AD 225 792).

22. U.S. Air Force Systems Command, Electronic Systems Division, Hanscom Field, Bedford, Mass., PACCS Command Support Center Advanced Planning and Conceptual Design Report, Volumes I thru IV, March 1962 (SECRET)

23. U.S. Army Corps of Engineers, Baltimore District, Feasibility of Nuclear Power for Underground Army Facilities, by Burns and Roe, Inc., 21 December 1962 (SECRET).

24. U.S. Army Corps of Engineers, "Design of Underground Installations in Rock, General Planning Considerations." EM 1110-345-431, 1 Jan 1961.

25. U.S. Army Corps of Engineers, "Design of Underground Installations in Rock, Protective Features and Utilities." EM 1110-345-435, 1 July 1961.

26. U.S. Army Corps of Engineers, "Heating and Air Conditioning of Underground Installations," EM 1110-345-450, 30 November 1959.

27. U.S. Atomic Energy Commission, "Nuclear Reactors Built, Being Built, or Planned in the United States." TID-8200. (Annual)

28. U.S. Atomic Energy Commission, "Costs of Nuclear Power", TID-8531 (Rev), Jan 61.

29. U.S. Atomic Energy Commission, "Nuclear Power and Utility Systems," TID-15329.

30. Von Ubisch. H., In Event of Reactor Disaster, What Protection Is To Be Gained by Constructing the Reactor Within A Rock Chamber? Translated by G. Varrows (U.K.A.E.A., Risley) (IGRL-TIR-90) from Tek. Tidskr 87, 893-8 (1957).